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Double Sided Interferometer, Profiling Measurement Simultaneously Yields Thickness and Form

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INTRODUCTION

Thickness measurements have been a basis for metrology since its inception and represent a fundamental technique for calibration of reference artifacts used world-wide, such as gage blocks. However, as materials and their applications have become more exotic, traditional contact based measurement techniques have become less applicable. In addition, quantification of from deviation between two surfaces has become more critical and usually requires a large point density to describe in detail. Optical probing or imaging techniques offer an alternative where there is little or no interaction with the part and can provide fast, accurate data for a large number of materials, but can be limited by reflectivity, acceptance angle seen by sensor and optical depth. A modular optical system adaptable to commercially available white light profilometers and optical coordinate measuring machines (CMMs) has been developed to measure absolute thickness and form.

For the purposes of this work "thickness" is defined as the distance between two points along a vector, such that the vector is normal to at least one surface of the sample under investigation.

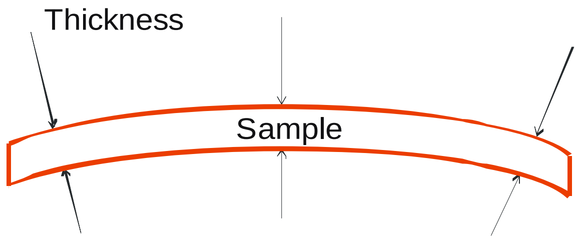

FIGURE 1. Absolute thickness of a foil or stacked sample is a combined measurement relating the upper and lower surface topography.

Samples of interest are nominally 2 mm - 8 mm in diameter and vary in thickness from 10 μm to 5 mm. Materials of interest include transparent and opaque solids such as polished metals and ceramics, but may also include low density metal and ceramic foams often combined as a laminate stack as illustrated in Figure 2. Surface finish requirements span from specular to having several micrometers of roughness. In addition, the quantification of engineered features formed into the surface, such as sine waves, have to be characterized. These features can represent upwards of 5.0% of the overall thickness of the free standing sample. Characterization of engineered surfaces and their relationship to the complete assembly is important to the overall understanding of these materials during dynamic deformation. The relationship between finish, form and thickness has to be quantified to 0.5% to 1.0% level.

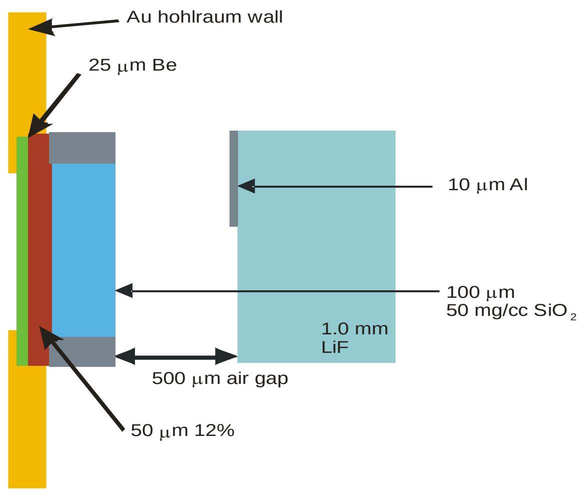

FIGURE 2. Typical assembly consisting of five stacked subassemblies. This assembly includes low density foam, metal and plastic foils and a partially coated tamper material with an ideal assembled thickness of 1.675 mm.

Because of the wide array of materials being studied at Lawrence Livermore National Laboratory (LLNL), no one measurement technique can be utilized exclusively. National

Laboratories [1,2], academia and industry [3] have spent a lot of effort trying to minimize measurement uncertainty utilizing a number of different techniques. For the most part these include some type of opposing probe technique where either a contact or optical probe pair oriented in opposing directions scan or image a sample and relate the two surfaces to a calibrated reference. Other measurement options include transmission based techniques [4] where some form of radiation is used in conjunction with material properties to determine thickness. The goal of the work is to adapt commercially available optical measurement systems to allow absolute thickness and form measurements.

DESIGN

The optical system was designed to be integrated into commercially available optical profilometer and/or CMM to optimize its value without limiting the instruments capability. The designed optical system consists of coated plane mirrors oriented such that the optical path lengths as seen by the optical probe are equal for both sides of the sample being investigated as shown in Figure 3. The turning mirrors are flat to 1/20th wave and have better than 1 nm S_a surface roughness.

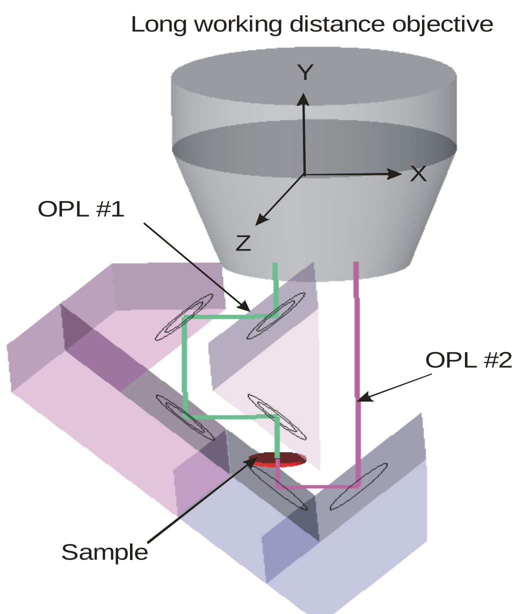

FIGURE 3. Modular optical system design showing top and bottom optical path length and long working distance objective.

In addition to matching the optical path lengths, the parallelism between the two paths is an important part of the measurement as it will introduce an apparent wedge into measurement data. In theory this error can be removed because it is stable and repeatable, but in practice the combined angular errors limit operation depending on the instruments optical probes numerical aperture and/or acceptance angle. It can also introduce lateral shifting between the front and rear surfaces causing a cosine error in absolute thickness.

To quantify the error attributed to the manufacture of the modular optical system a set of homogenous transformation matrices (HTMs) [5] were derived using small angle approximations. In this case, the reference coordinate system is defined by the objective of the optical probe. Each mirror is represented by the combination of three rotations and one translation matrix in the form of,

$$\mathbf{T_m} = \begin{bmatrix} \mathbf{R_m} & \mathbf{V_m} \\ 0 & 1 \end{bmatrix}. \tag{1}$$

Assuming small angles and removing second order terms the rotation matrix (**R**$_\mathbf{m}$) for each mirror can be expressed as,

$$\mathbf{R_M} = \begin{bmatrix} C(\alpha_m) - \varepsilon_z S(\alpha_m) & \varepsilon_z C(\alpha_m) - S(\alpha_m) & \varepsilon_y \\ S(\alpha_m) + \varepsilon_z C(\alpha_m) & C(\alpha_m) - \varepsilon_z S(\alpha_m) & -\varepsilon_x \\ \varepsilon_x S(\alpha_m) - \varepsilon_y C(\alpha_m) & \varepsilon_y S(\alpha_m) + \varepsilon_x C(\alpha_m) & 1 \end{bmatrix}, \tag{2}$$

where α_m is the reflected beam angle (2 times the angle of incidence on the mirror), ε_x, ε_y and ε_z are the angular alignment errors about the x-, y- and z-axes respectively.
The vector **V**$_\mathbf{m}$ is the translation vector between each mirror coordinate system given by,

$$\mathbf{V_m} = \begin{Bmatrix} a_m \\ b_m \\ c_m \end{Bmatrix}. \tag{3}$$

Transforming the optical paths back to the reference coordinate system is given by,

$$\{\mathbf{I}\}_{\mathbf{ref}}^{\mathbf{OPL1}} = {}^{\mathbf{ref}}\mathbf{T_1}\ {}^{1}\mathbf{T_2}\ {}^{2}\mathbf{T_3}\ {}^{3}\mathbf{T_4}\ \{\mathbf{I}\}, \tag{4}$$

$$\{\mathbf{I}\}_{\mathbf{ref}}^{\mathbf{OPL2}} = {}^{\mathbf{ref}}\mathbf{T_5}\ {}^{5}\mathbf{T_6}\ \{\mathbf{I}\}, \tag{5}$$

where {**I**} represents the vector normal to the image plane from each reflective surface. By transforming the image plane location back through the front (OPL #1) and rear optical paths (OPL #2) and comparing to the ideal path, the errors between paths can be represented. The difference between equations (4) and (5) show that the angular errors multiplied by the offset distances of each path length when summed individually relative to the sample image plane must be minimized to maintain parallelism. The detailed analysis is left as an exercise for the reader. Based on the analysis described above, a design specification of 70 μrad about the x- and z-axes was used to define the parallelism between the upper and lower beam paths.

RESULTS

To calibrate and determine performance of the apparatus a 100 μm gage block with a thickness uncertainty of ± 0.25 μm was used a reference artifact. The front and rear surface of the sample were scanned using the double sided optical system highlighted above (see Figure 3).

Two commercial based systems were used to evaluate thickness. The first was a Nikon NEXIV VMR 3020 optical measuring machine. The front and rear surfaces of the gage were scanned in two orthogonal directions using a laser confocal probe. The manufacturer stated uncertainty in the z-direction is 1.5 μm for the scan lengths used in this experiment. Results of a sample measurement are shown in Figure 4. In this case we measured an average thickness of 103.4 μm with a standard deviation of 2.6 μm.

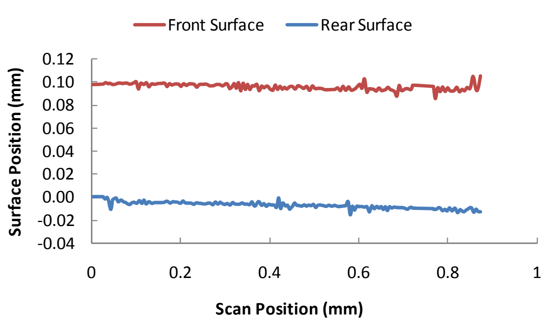

FIGURE 4. Thickness measurement of 100 μm gage block using a Nikon NEXIV VMR 3020 optical measuring machine*.*

The second measurement system evaluated was a Veeco NT8000 white light surface profilometer. Analogous to the Nikon instrument, both the front and rear surface of the gage were scanned using the double-sided optical system. Manufacturer stated uncertainty for long-range scanning in the z-direction for the optical profilometer is 0.05% of the scan range (50 nm). 2D images representing the front and rear surfaces of the gage are shown in Figure 5a. Figure 5b shows a line trace across both the front and rear surface of the gage block. The calculated average thickness was found to be 104.5 μm a standard deviation of 0.5 μm.

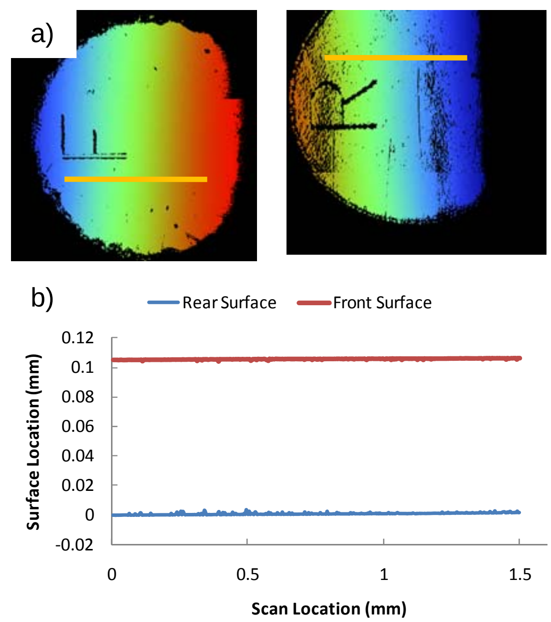

FIGURE 5. a) Profiles of front and rear surfaces of the gage block as measure by the profilometer. b) Line trace data from the optical profile showing the thickness of the gage block at 104.5 μm.

There are two predominant sources of uncertainty with the white-light profilometer and optical CMM. The first is the parallelism of the optical paths, which can be calibrated and removed in software as discussed earlier. Optical path angular deviation of the prototype system was measured to be ~110 μrad and accounts for the slope variation between front and rear surface measurements.

The second is the location of the "zero" plane where OPL #1 and OPL #2 are equal. Because the location of the part mid-plane is independent of the “zero” plane location, the absolute thickness can appear to be thick or thin depending on where the sample lies within the optical path. Ideally, the mid-plane of the sample would be aligned with the “zero” plane of the optic resulting in a “true” measured value. For the optical CMM, this is part of the calibration process and is removed mathematically. In the case of the profilometer, the z-location can also be derived from the calibration artifact and included in the thickness analysis. However, the absolute z-location for each scan is reset between scans, which add to the overall uncertainty of the measurement. Again, in theory this can be removed mathematically, but relies on stage, optical package and sample holder stability. At present these uncertainty sources are under investigation.

SUMMARY

A modular optical system has been designed and prototyped for measuring the absolute thickness of samples ranging in thickness from 10 μm to 5 mm with a diameter of upwards of 8 mm. This optical package was evaluated on two commercial measuring systems using a 100 ± 0.25 μm calibrated gage block as a reference. A Nikon NEXIV optical CMM measured a thickness of 103.4 μm with a 2.5 μm standard deviation; while the Veeco NT8000 white-light profilometer measured a thickness of 104.5 μm with a standard deviation of 0.5 μm. Although the white-light profilometer is potentially more accurate, due to the displacement laser interferometer positional feedback in the z-axis, the combination of optical package, sample mount and machine stability coupled with the z-location of each scan being reset between front and rear scans, adds significantly to overall measurement uncertainty.

Work continues on evaluating the stability limit of the optical system and sample mount. Also, modification to the commercial software to allow tracking of the z-axes during multiple scans is being addressed with the manufacturer.

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- Erik Novak (Veeco), Greg Maksinchuk (Veeco), Phil Castle (Nikon)

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